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MODEL STUDIES OF LARGE VENTED OPENINGS - PHASE II

BY

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
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MODEL STUDIES OF LARGE VENTED OPENINGS - PHASE II

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ABSTRACT

A study was made of the optimum location for blast protection of generators in pits and shelters. The factors considered were cost, blast overpressure, dynamic pressure, operational dependability, and cooling air requirements. Ground shock and radioactivity were not considered.

Representative locations and arrangements studied were: (1) open pit (2) pit covered with grating (3) pit covered with filter (4) underground shelter (5) room adjoining shelter (6) separate underground compartment and (7) building above ground.

As it could be expected underground locations give the most protection but are the most expensive. Least expensive is the open pit, which gives the least protection. If the above-ground building can withstand the overpressure, it is as effective a location for generators as the underground compartment.

Heat, noise, vibration and exhaust create problems when generators are located within shelters. Open pits with gratings provide economical protection from dynamic pressure. A filter cover using compressible cylinders should provide sufficient protection at moderate cost, but needs further development.

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INTRODUCTION

The previously reported Phase I¹ determined the optimum configuration of generator and equipment pits to protect them against blast loading. Phase II (herein reported) evaluates the protection provided by several pit, underground, and above ground arrangements for housing generators and indicates the relative cost of each. Operational dependability and cooling air requirements are also considered. It was not possible to include the effects of ground shock and radioactivity in this report. It is hoped that the cost figures will enable a designer to decide whether a given situation requires an expensive underground installation or a much less expensive open pit arrangement.

Seven generator locations were studied: (1) open pit, (2) pit with ventilating cover, (3) pit with filter cover, (4) underground shelter, (5) underground compartment connected to shelter, (6) separate underground compartment, and (7) special building above ground. These names are descriptive, but a few require further definition:

Open pit -- no parapet, no cover

Pit with ventilating cover -- a grating, matrix of holes, louvers, or similar devices¹. Ventilation is provided by natural air circulation and by the generator fan only, no separate ventilation being required.

Filter cover -- a layer₂ of filter material such as sand or possibly compressible cylinders. Ventilation is provided by a separate forced air circulation unit.

Cost estimates are given in Appendix A for typical examples of the different locations. These estimates, based on construction designed to withstand overpressures of at least 100 psi, will vary according to geographical region, soil, weather, etc. Costs will also change as design details are resolved, and may be lower if any of the designs are produced in large quantities.

In this note, the term "generator" includes both the electrical generator and the driving mechanism (usually a diesel or a gasoline engine). The average small generator is 2 to 2½ feet wide, 3 or 4 feet high, and 5 or 6 feet long; therefore, the compartment size selected for computing the estimates was 9 by 12-feet by 7-feet high.

This size provides a 3-foot working space around the generator and also provides space for storage of fuel, oil, and essential maintenance equipment. Experience shows that the natural ventilation will be adequate in open or grating covered pits. In operation Plumbbob³, 15 kw generators were operated in much smaller pits (5 by 10 feet, 5½ feet deep) covered by a grating.

Construction estimates included in this note are based on interior pit dimensions of 9 x 12-feet, 7-feet deep, which are sufficient for 10 kw generators of most of the makes. The ventilation requirements are also based on the 10 kw generator, which is considered ample for a 100-men shelter.

During the Operation Plumbbob tests in Nevada³, a gasoline-driven generator was placed in each of six pits. All six generators were operable before the blast. In two of the pits, overpressures reached 100 psi; in the other four, 60 psi. All six generators were damaged, and only one (60 psi overpressure) was operable after the test. The damage was minor in the sense that repairs could be made easily, but major in the sense that during an attack, repairs would be too time consuming. Reference 3 tabulates the damage from the Nevada tests and attributes some 50 instances of damage to dynamic pressure and about 17 to overpressure. Thus, according to the conclusions from Phase I¹, approximately 75 percent of the damage should be eliminated by using a suitable ventilating cover. Unfortunately the gratings that covered the pits were torn loose during the Nevada tests, and the protection they gave to the equipment cannot be assessed.

Open Pits and Pits with Gratings

The protection offered by the open pit is quite limited as there will be little or no protection from overpressure and only moderate protection from dynamic pressure¹. Since most generators are ruggedly built, the open pit may have application in "unhardened" construction. The addition of a grating, however, will greatly improve the protection from dynamic pressure and its use should be considered whenever an open pit installation is contemplated.

The cost of a 9 by 12 by 7-feet open pit is about \$2,300 (see Appendix A). A grating over this pit would increase the cost by \$1,100 or \$1,200 largely because of the structural steel necessary to support the grating.

Other characteristics of the open pits and pits with gratings are:

a. In the open pit, the equipment is easily accessible for maintenance and removal. If covered with a grating, a section could be removable for personnel entry and exit.

b. Equipment in pits with gratings will be protected from flying objects.

c. The remote location eliminates generator noise and vibration in the shelter.

d. Leaves, branches, dirt, and other debris will collect in the open pit. A grating would keep out some of the larger debris.

e. Whether the pit is open or grating-covered the generator is exposed to the effects of weather; and the pit will accumulate rain water, which would have to be pumped out unless a gravity drainage system can be installed. A shed over the pit would keep the rain out until a blast destroyed the shed. The cost of rain water protection has not been included in the estimates.

Pits With Filter Covers

Although an unlimited number of filter covers can be designed for a generator pit, NCEL studies have included the use of sand and compressible cylinders. These studies, however, were made for another purpose, but the use of either for covering generator pits is worthy of consideration. A grating does not reduce overpressure, but a thick layer of sand has a large number of small, irregular passageways which will reduce the overpressure. A thick layer of compressible plastic cylinders allows the air to pass through the interstices between the cylinders rather than through the material itself². Overpressure will compress the cylinders and close off these interstices. A layer of sand, compressible cylinders, or any other filter cover, should reduce the dynamic pressure to practically zero.

The compressible cylinders appear to be a more practical filter than sand in reducing blast pressures. The protection afforded by sand is very dependent on grain size and compaction, and sand is difficult to hold in place. Also, a more powerful ventilation system will be required to draw air through the sand.

A layer of nonporous, compressible cylinders, one-square foot in area and one-foot deep, allows 110 cfm of air to pass through if the pressure across the filter is 1/2-inch water gage². The area of the filter has to be about 23.5-square feet in order to pass 2,600 cfm of air (see Appendix B). Another filter of the same size is necessary to allow heated air to leave the pit, and this requires an additional 1/2-inch of water gage pressure. Figure 1 is a drawing of a pit using this cover. Tests made by J. M. Stephenson² indicate this filter arrangement reduces the overpressure in the pit to 7 or 8 psi when outside overpressure is 100 psi. This overpressure is

considered low enough so that the generators will remain operable during and after the blast. Further, it will not be a shock, but will rise quite gradually.

Generator exhaust must be vented out of the pits; otherwise, the heat will increase the air-cooling requirements, the extra cost of which will exceed the cost of a separate exhaust outlet even when blast protection is necessary. Also, exhaust fumes are dangerous, and the quantity of cooling air is probably insufficient for safe breathing inside a covered pit (see Appendix C).

The filter cover excludes dirt and debris from the generator pit. However, the filter must be cleaned occasionally or ventilation will be impaired. Filter covers should provide good protection from flying objects and weather (except rain).

Rain water could seep through and accumulate in the pit, and as with the open pit, drainage or pumping facilities must be provided. Rain water will probably be held in the interstices of the compressible cylinders and will certainly be held by sand. The effect would be an increase in the load on the structure and an increase in the pressure drop across the filter.

Personnel access is best provided by a small, removable section.

Without blast protection on the exhaust, the compressible-cylinder cover costs about \$5,400 (Appendix A) as compared to \$3,400 for the grating cover. The filter cover requires a blower, an extra grating to hold the cylinders in place, some duct work, and a few other items that the grating cover does not require; but the compressible cylinders, estimated at \$1,000, are half of this additional cost. The cylinders might cost less if purchased in large quantities.

The advantages of this arrangement suggest that it might be a good compromise between (1) the inadequacies of the open and grating-covered pits and (2) the high cost of underground protection. It is realized, however, that additional development will be necessary before the compressible cylinder cover can be regarded as a workable arrangement.

Underground Locations

Three underground locations for generators are considered in this note: (1) the shelter itself, (2) an adjoining room entered from the shelter, and (3) a separate room with a separate entrance.

GENERATOR IN SHELTER

If the generator is located in the shelter itself, reduced construction costs result in a saving of about \$2,000 over that of the separate underground compartment. However, since the heat from the generator must now be removed so that the temperature in the shelter does not rise above that required by the occupants, there will be an increased ventilation requirement. The cost of this increased ventilation will more than off-set the saving in construction costs.

For example, suppose that the shelter designer has selected a set of conditions suitable to the occupants of the shelter. If a generator is now placed in the shelter, the ventilation rate must be increased so that the conditions in the shelter are not changed appreciably. Suppose the air entering the shelter is 10° cooler than the ambient temperature in the shelter. It will require 5,200 cfm (Appendix B) of this air to remove the extra 55,600 btu/hr of heat given off by the generator and maintain the same ambient temperature. Reference 4 contains a number of ventilation packages which vary in cost from 53 cents per cfm to \$1.10 per cfm. If a combination costing 80 cents per cfm is chosen, it will require \$4,160 to provide the extra 5,200 cfm of cooling air which is necessary to keep the shelter suitable for the inhabitants while the generator is operating. To this \$4,160 must be added \$5,200 for blast protection. Were the generator located in a separate compartment where only 2,600 cfm of air at 100 - 110°F is needed to maintain an ambient temperature of 120 - 130°F around the generator, the corresponding cost would be about \$700 plus \$2,600 for blast protection making a total of \$3,300 as compared to \$9,360 for the generator in the shelter.

Although this example may not be the most economical and the figures used are based on supposition, it does show, and this is the important point, that locating the generator in the shelter will be expensive because the cooling air must be conditioned to the requirements of the shelter occupants rather than to the cooling requirements of the generator.

Generators inside the shelter would cause other problems:

- a. Noise would be excessive.
- b. Vibration would have to be reduced.
- c. Exhaust gases might contaminate the air.

Because other locations eliminate these problems and because of the high cost of cooling, this location was not considered further.

GENERATOR IN SEPARATE OR ADJOINING ROOM

A better location for the generator is in a separate compartment or in an adjoining room connected to the shelter by a short passageway (about 10 feet long). The cost saving of using an adjoining room rather than a separate compartment (\$7,400 as compared with \$9,500) is due largely to the consolidation of ventilation systems. Appendix B shows that 2,600 cfm of air at 100 to 110°F is needed to keep the generator from overheating. Thus, were the temperature of the air leaving the shelter 100°F (and it will probably be much lower), 2,600 cfm would be necessary to cool the generator. This rate of flow may be a little high for a 100-man shelter, but the air leaving will probably be cooler than 100°F. Were it 90°F, only 1,850 cfm would be needed. Thus, by either increasing the airflow or reducing the temperature, it should be easy to design the shelter complex so as to cool the generator with air from the shelter.

The oxygen requirements of such an arrangement should not present any problems. Diesel-driven generators of 10 kw need less than 80 cfm of air for combustion (see Appendix D), and gasoline-driven generators require about half this amount. Since the air required for personnel in a 100-man shelter is much less than that required to control the temperature, there will be sufficient oxygen for generator operation.

To reduce noise in the shelter, a door to the generator compartment is recommended. It is suggested that the door be made of metal so as to protect the shelter if a fire starts in the generator room. It need not be capable of withstanding 100 psi.

The completely separate generator compartment (Figure 2) has the advantages of an adjoining room except for access from the shelter. The cost is greater because the shelter ventilation system cannot be used, and separate entry would be necessary. The separate compartment will usually be desirable when one power unit serves several shelters. This would reduce both construction and ventilation costs per kilowatt of installed power.

All three underground arrangements increase generator protection; weather protection is inherent. Debris can accumulate near surface vents but is easily removed. However, unless a filter is used, dust can enter the compartment with the ventilation air. The cost figures do not include a filter, as it is not believed to be necessary, but arrangements using shelter air would automatically have a filter. Ordinary maintenance should keep the generator in good operating condition. The underground compartments give complete protection from flying objects.

In all of the underground arrangements, a separate exhaust outlet is necessary because the ventilation systems specified are not designed to handle the extra heat from the exhaust. Besides being less expensive, the separate outlet would eliminate the hazard from exhaust fumes (Appendix C).

The cost figures assume that when the generator compartment is accessible through a shelter, the shelter entrance is large enough to bring in or remove the generator. In the design of the separate compartment, the hatch limits the size of generator that can be removed.

Buildings Above Ground

An above-ground generator compartment would be necessary where underground construction is not feasible. Figure 3 shows a design which costs about \$10,000, approximately \$500 more than the separate underground compartment. The building is a 14-foot diameter hemispherical shell of 1/4-inch steel covered with a 10-inch thickness of reinforced concrete. Because of its shape, its size cannot be compared directly with the other six arrangements. There is more floor space, but height is limited over much of this area.

Ventilation requirements are no different from those of the underground compartments. Operational dependability of the generator depends on care and maintenance rather than on the adverse effect of weather elements. Dirt, debris, and flying objects are no problem. The generator size is limited only by the size of the entrance door. The advantages and disadvantages of the above-ground building are similar to those of the separate underground compartment.

FINDINGS AND CONCLUSIONS

Tables I and II summarize the advantages and disadvantages of the seven-generator housing arrangements studied. All of these structures were designed to withstand a 100-psi overpressure blast. The studies show that if cost is low, protection is low, and as cost increases, so does protection. But it was not anticipated that it would be so expensive to put the generator in the shelter with the occupants.

The generator is more reliable when protected from weather, dirt, debris and flying objects. In open or grating-covered pits, more frequent cleaning and maintenance is essential, increasing maintenance cost and decreasing reliability.

Accessibility to personnel is good in all of the arrangements. Removal and replacement of the generator will be limited by entrance size in the underground arrangements and in the building above ground. Removal and replacement of generators installed in pits will require the removal of any gratings or covers.

Disturbances to personnel in the shelter are problems which are solved when the generator compartment adjoins the shelter or is separate. However, these problems are difficult to solve if the generator is housed in the shelter itself.

The exhaust gas hazard depends on physiological effects; the specification of a safety limit is arbitrary. It is reasonable to expect that natural ventilation would alleviate the hazard in the open pit. In the other arrangements, separate exhaust outlets should be provided.

Of the seven arrangements, the room adjoining the shelter is best if each shelter has its own generator, but the separate compartment would usually be used for a control power plant serving several shelters. A filter-covered pit using compressible cylinders offers good and economical protection, but needs further investigation. The open pit does not give much protection, but the grating-covered pit reduces dynamic pressure to a low value, and since generators are ruggedly built, it should be useful in many "less-hardened" installations. The generator should not be placed in the shelter with the occupants. An above-ground building need be considered only if underground construction is impractical.

TABLE I
Rating Comparison of Housing Arrangements for Shelter Generators*
Protection and Reliability Characteristics

Location	Cost Rating	Protection from Blast Overpressure	Protection from Blast Dynamic Pressure	Protection from Flying Objects	Protection from Large Debris and Branches	Protection from Dirt	Reliability of Generator
Open Pit	1	5	4	5	5	5	4
Grating-Covered Pit	2	5	2	2	2	5	3
Filter-Covered Pit	3	2	1	1	1	2	2
Underground, in Shelter	5	1	1	1	1	1	1
Underground, Adjacent to Shelter	4	1	1	1	1	1	1
Underground, Separate from Shelter	5	1	1	1	1	2**	1
Above Ground	5	1	1	1	1	2**	1

* Ratings: 1 = Lowest cost, greatest protection, higher reliability, etc.
2,3,4 = Intermediate gradations, 2 being better than 3, etc.
5 = Highest cost, least protection, lowest reliability, etc.

** Rating 1 if dust protection (filter) is used.

TABLE II
Rating Comparison of Housing Arrangements for Shelter Generators*
Convenience, Comfort and Safety Characteristics

Location	Accessi- bility to Personnel	Capability for Equip- ment Removal	Noise Dis- turbance	Vibration Disturbance	Exhaust Hazard to Personnel**	Exhaust Hazard to Repairmen**
Open Pit	1	1	1	1	1	1
Grating-Covered Pit	2	3	1	1	1	2
Filter-Covered Pit	2	3	1	1	1	3
Underground, in Shelter	1	2	5	5	5	5
Underground, Adjacent to Shelter	1	2	2	2	2	3
Underground, Separate from Shelter	2	4	1	1	1	3
Above Ground	1	2	1	1	1	3

* Ratings: 1 = Easiest accessibility, least disturbance, least hazard, etc.
2,3,4 = Intermediate gradations, 2 being better than 3, etc.
5 = Most difficult accessibility, most disturbance, greatest hazard, etc.

** Hazard refers to danger from exhaust leaks; this is greater in the shelter (where the con-
centration of CO₂ is already high) than in the separate compartments.

Appendix A

COSTS FOR LOCATIONS STUDIED

In this cost comparison of open pits, underground compartments, and above-ground buildings for housing generators, the figures are reasonable estimates for a compartment 9 by 12 feet in plan and 7 feet high. If the compartment is underground, its roof is 5 feet below the surface.

Figure 1 is an open pit with a filter cover; Figure 2 is a separate underground compartment; and Figure 3 is a compartment built above ground. From Figure 1, the design of the completely open pit and of the grating-covered pit can easily be determined. From Figure 2, the extension of the shelter to include the generator, and the design of the compartment adjoining the shelter can be determined.

The 9 by 12 feet pit allows room for a small diesel generator (5 to 20 kw). Most small generators are 24 to 30 inches wide, but the length increases with the output. Thus, a 5 kw generator may be 3 feet long, and a 20 kw generator may be 6 to 6½ feet long⁵. Working space around generators must be 30 to 36-inches for repairs and for storage of fuel and maintenance equipment. For these reasons, the 9 by 12 feet plan was selected. The computations allow a wall thickness of one-foot and an additional six-inches for forms to hold the concrete in place while curing.

The estimates for the various locations are given in some detail so that if the design is altered, the cost figures can be adjusted accordingly. It is possible that features have been included which can sometimes be eliminated. In the case of the generator inside the shelter or in an adjacent compartment, there is considerable dependence on the shelter design and the cost of an actual installation can vary widely.

The cost of blast protection using BUDOCKS or Mosler valves is estimated at \$1.00 per cfm of cooling air. The allowance of \$200.00 for blast protection on the generator exhaust can be eliminated if further research shows that blast protection is unnecessary. If the exhaust is vented directly to the outside, the cost would be only \$5.00 or \$10.00, because 100 psi pipe is about \$1.00 per foot.

Open Pit (design adapted from Figure 1)

If walls are one-foot thick, plus 6-inch forms, and a 15-inch thick base, costs are:

Excavation:

$$\frac{12' \times 15' \times 8.25'}{27} = 55 \text{ cu yd at } \$4.50 \quad \$ 250.00$$

Backfill:

$$55 - \frac{11' \times 14' \times 8.25'}{27} = 8 \text{ cu yd at } \$1.50 \quad 12.00$$

Compaction:

$$8 \text{ cu yd at } \$1.50 = 12.00$$

Concrete (in place):

$$\frac{11' \times 14' \times 8.25'}{27} - \frac{9' \times 12' \times 7'}{27} = 19 \text{ cu yd at } \$60.00 \quad 1140.00$$

Reinforcing steel (in place):

500.00

Subtotal

\$1,914.00

10% overhead & 10% contingency

382.00

Total

\$2,296.00

Open Pit with Grating Cover (design adapted from Figure 1)

The grating and supporting beams will add about 1 foot 5 inches to the depth; other dimensions are same as for open pit.

Excavation:

$$\frac{12' \times 15' \times 9.66'}{27} = 64.5 \text{ cu yd at } \$4.50 \quad \$ 290.00$$

Backfill:

$$\frac{12' \times 15' \times 9.66'}{27} - \frac{11' \times 14' \times 9.66'}{27} = 10 \text{ cu yd at } \$1.50 \quad 15.00$$

Compaction:

$$10 \text{ cu yd at } \$1.50 \quad 15.00$$

Concrete (in place):

$$\frac{11' \times 14' \times 9.66'}{27} - \frac{9' \times 12' \times 8.417'}{27} = 21.6 \text{ cu yd}$$

at \$60.00 \$1296.00

Reinforcing steel (in place): 500.00

Grating (installed): 128.00

Structure steel to support grating: 3000 lb at \$0.14 420.00

Fabrication of support: 200.00

Subtotal \$2,864.00

10% overhead & 10% contingency 574.00

Total \$3,438.00

Covered Pit using Compressible Cylinders (Figure 1)

Since two gratings are required, the depth of the pit is 1 inch more than that of the grating-covered pit without compressible cylinders, but this will make little difference in the estimate.

Two gratings with support:¹ \$2,996.00

Hardware cloth, $\frac{1}{4}$ " mesh, 23 gage:

2(10' x 13") = 260 sq ft at \$0.06 15.00

Fan with motor, 3,000 cfm at 1" static pressure, 1½ hp

(installed and connected to generator): 400.00

Compressible cylinders: 1,000.00

Duct work, 18 gage, galvanized, 100 sq ft (installed) 66.00

Blast protection on exhaust (if necessary): 200.00

Subtotal \$4,677.00

10% overhead and 10% contingency 935.00

Total \$5,612.00

Inside shelter (design adapted from Figure 2)

It is assumed that the shelter and generator compartment are of the same type of construction so that there are no problems in enlarging the shelter to include the generator or in increasing the size

¹See subtotal of costs for open pit with single grating.

in the original design. The ceiling is an arch similar to that used in the separate underground compartment. One wall is unnecessary, but the floor space is still 9 by 12 feet. A 9 foot wall is eliminated rather than a 12 foot wall so that the ceiling span will be less. The walls are vertical up to 3 feet above the base and are 1 foot thick except that the base is 15 inches thick. Because of the increased depth of excavation and because of the shape of the compartment and ventilators, some of the unit cost figures are a little higher for underground construction than they are for ground-level pits.

Excavation:

$$\frac{12' \times 13\frac{1}{2}' \times 14.25'}{27} = 85.5 \text{ cu yd at } \$5.00 \quad \$ 428.00$$

Backfill:

$$85.5 - \left[\frac{11' \times 4.25' + \frac{(3.14)}{2} \times 11'}{27} \right] \times 13' \times 0.2' = 54.5 \text{ cu yd at } \$1.50 \quad 82.00$$

Compaction:

$$54.5 \text{ cu yd at } \$2.00 \quad 109.00$$

Concrete (in place):

$$\text{Base } 11' \times 13' \times 1.25' = 179 \text{ cu ft}$$

$$\text{Wall } (3' \times 13' \times 1') \times 2 = 78$$

$$\text{Ceiling } \frac{3.14 \times 10 \times 13}{2} = 204$$

$$\text{End } \frac{(3.14) \times (4.5)^2 (1)}{2} + 3 \times 9 \times 1 = \frac{59}{2} \text{ cu ft or } 19.25 \text{ cu yd at } \$70.00 \quad \$ 1350.00$$

Reinforcing steel (in place):

800.00

Duct work:

25.00

Shelter ventilation (Increase in shelter ventilation to cool generator. Cost is very dependent on shelter ventilation and may be higher or lower according to the austerity desired in

¹The 0.2 cu yd is an allowance for space required for exhaust outlet.

the shelter) .5200 cfm at \$0.80 per cfm¹. \$ 4160.00

Additional blast protection because of increased ventilation 5200.00

Separate exhaust outlet for generator, including blast protection (installed): 200.00
 Subtotal \$12,354.00
 10% overhead & 10% contingency 2,471.00
 Total \$14,825.00

Underground Compartment Connected to the Shelter (design adapted from Figure 2)

The passageway is assumed to be 10 feet long, 3 feet wide, and 7 feet high, with 1 foot thick walls.

Excavation:

$$12' \times 15' \times 14.25' = 2,565 \text{ cu ft}$$

$$6' \times 10' \times 14.25' = \frac{855}{3,420 \text{ cu ft or } 127 \text{ cu yd at } \$5.00} \$ 635.00$$

Backfill:

$$2565 - (11' \times 14')(4\frac{1}{2}') - \frac{\pi (5.5')^2}{2} (14') = 1,246 \text{ cu ft}$$

$$(14\frac{1}{2}') (6' \times 10') - (9\frac{1}{2}') (5') (10') = \frac{393}{1,639 \text{ cu ft or}}$$

$$61 \text{ cu yd at } \$1.50 \quad 92.00$$

Compaction: 61 cu yd at \$2.00 122.00

Concrete (in place):

$$\text{Compartment: Base } 14' \times 11' \times 1\frac{1}{4}' = 193 \text{ cu ft}$$

$$\text{Walls } (3' \times 14' \times 1') \times 2' = 84$$

$$\text{Ceiling } \pi \frac{(10' \times 1' \times 14')}{2} = 220$$

$$\text{Ends } \left[\frac{\pi (4.5')^2 (1')}{2} + (3') (9') (1') \right] \times 2 =$$

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¹ Interpolated from figures in reference 4.

Less door openings $3 \times 7 \times 1 = -21$, net 594 cu ft

Tunnel: Base $10' \times 1\frac{1}{2}' \times 5' = 63$ cu ft

Walls $10' \times 7' \times 1' \times 2 = 140$

Ceiling $10' \times 5' \times 1' = 50$, net 253 cu ft

$\frac{594 + 253}{27} = 31.4$ cu yds at \$70.00 \$2200.00

Metal door between compartment and shelter (installed): 150.00

Reinforcing steel (in place): 1000.00

Shelter ventilation (additional amount to cover increase in cooling air. Cost is very dependent on shelter ventilation and might even be eliminated by a coordinated design. Figures given are based on a 1000 cfm increase over shelter requirements such as from 1600 cfm to 2600 cfm) 1000 cfm @\$0.80 per cfm¹ 800.00

Additional blast protection (because of airflow increase): 1000.00

Separate exhaust outlet, including blast protection (installed): 200.00

Subtotal \$6199.00
10% overhead and 10% contingency 1240.00
Total \$7439.00

Separate Underground Compartment (Figure 2)

Excavation:

$12' \times 15' \times 14.25' = \frac{2565}{27} = 95$ cu yd at \$5.00 \$ 475.00

Backfill: Walls $14' \times 11' \times 4\frac{1}{2}' = 654$ cu ft

Ceiling $\left[\frac{\pi(5.5)^2}{2} \right] \times 14' = 665$

Entrance (neck) $\pi (2 \frac{2}{3})^2 (3') = 67$

Entrance (top) $7' \times 7' \times 1\frac{1}{2}' = 73$

¹Interpolated from figures in reference 4.

$$\text{Ventilators } \left[\pi \frac{(7')^2}{(12')^2} \right] \times (2\frac{1}{4}') \times 2 = 5$$

$$\text{Ventilators } \pi (1.25)^2 \times 2' \times 2 = \frac{20}{1484 \text{ cu ft}}$$

$$2,565 - 1,484 = 1,081 \quad \frac{1081}{27} = 40 \text{ cu yd at } \$1.50 \quad \$ 60.00$$

Compaction: 40 cu yd at \$2.00 80.00

Concrete (in place):

$$\text{Base } 14' \times 11' \times 1\frac{1}{4}' = 193 \text{ cu ft}$$

$$\text{Walls } (14' \times 3' \times 1') \times 2 = 84$$

$$\text{Ceilings } \left[\frac{\pi (10') (1')}{2} \right] 14' = 220$$

$$\text{Ends } \left[\pi \frac{(4.5')^2 (1')}{2} + (3') (9') (1') \right] \times 2 = 118$$

$$\text{Hatch } \left[\pi (2 \frac{2}{3}')^2 \right] \times 3' = 67$$

$$7' \times 7' \times 1.5' = 74$$

$$- \left[\pi (2')^2 \right] \times 5.5' = \frac{-69}{687 \text{ cu ft}}$$

$$\frac{687}{27} = 25.4 \text{ cu yd at } \$70.00^1 \quad 1820.00$$

Reinforced steel (in place): 850.00

Hatch cover, 4 foot diameter clear opening, 100 psi rated (fabricated and installed): 1000.00

Miscellaneous steel:

$$\text{Angles } 2' \times 2' \times \frac{1}{4}', 22 \text{ ft at } 3.2 \text{ lb per ft} = 70.4 \text{ lb}$$

$$\text{Bar } \frac{1}{4}" \text{ round, 15 ft at } 64 \text{ lb per ft} = \frac{10}{80.4 \text{ lb}}$$

$$\text{at } \$0.15 = \quad 12.00$$

¹ 26 cu yd used because the ventilation installation will require additional cement.

Schedule 10 pipe, 14", 20 ft at \$5.00	100.00
Fabrication	40.00
Fan with motor, 3,000 cfm at 2' static pressure, 3 hp (installed and connected to generator):	650.00
Duct work: 18 gage, galvanized, 20 ft, installed:	25.00
Blast protection on ventilation (installed):	2600.00
Blast protection on exhaust (installed):	200.00
Subtotal	\$7912.00
10% overhead & 10% contingency	1582.00
Total	\$9494.00

Compartment above Ground (Figure 3)

When underground construction is not feasible, the generator can be housed above ground. The hemispherical shape chosen is structurally strong, with a minimum of airflow resistance.

Excavation:

$$(3.14 \times 10.5'^2) \times 1.333' = 461 \text{ cu ft or } 17.1 \text{ cu yd}$$

at \$3.50 60.00

Backfill:

$$461 - (3.14 \times 10'^2) \times 1.085 - 3.14 (9.38')^2 \times 0.25' = 51 \text{ cu ft, } \frac{51}{27} = 2 \text{ cu yd at } \$1.50$$

3.00

Compaction: 2 cu yd at \$1.50 3.00

Concrete (in place):

$$\text{Base (lower part)} = \pi (10')^2 \times 1.085' = 341 \text{ cu ft}$$

$$\text{Base (upper part)} = \pi (9.38')^2 \times 0.25' = 69$$

$$\text{Spherical sector} = \frac{2\pi r^2 \theta}{3} = \frac{2\pi r^3}{3} (1 - \cos \theta) = \frac{\pi}{3} (8')^3 = 536$$

Truncated sections:¹ $r_1 = 8' (.866) = 6.93'$

$$h_1 = 6.93 \tan 60^\circ = (6.93) (1.732) = 12'$$

$$r_2 = \frac{8}{.866} = 9.24$$

$$h_2 = 9.24 \tan 60^\circ = (9.24) (1.732) = 16'$$

$$\frac{1}{3} \pi [r_2^2 h_2 - r_1^2 h_1 - r_1^2 (h_2 - h_1)] =$$

$$\frac{\pi}{3} [(9.24)^2 (16) - (6.93)^2 (12) - (6.93)^2 (4)] = \frac{627}{1573} \text{ cu ft}$$

Inner sphere

$$\frac{2}{3} \pi r^3 = \frac{2}{3} (3.14) (7.146)^3 = 763 \text{ cu ft}$$

$$\text{Door } 17 \text{ cu ft} = \frac{17}{780} \text{ cu ft}$$

$$1573 - 780 = 793 \text{ cu ft or } 29.4 \text{ cu yd at } \$70.00 \quad \$2060.00$$

Reinforcing steel (in place): 1000.00

Hatch door, 3' x 4' clear opening, 100 psi-rated (fabricated and installed). 1000.00

Compartment lining:

$$\frac{1}{4}" \text{ steel plate, } 2\pi r^2 = 2(3.14) (7.156)^2 = 322.7$$

$$\text{plus extension below ground level, } \frac{1}{4} (2\pi) (7.156) = \frac{11.3}{334.0}$$

$$334 \text{ sq ft, } \frac{1}{4}" \text{ steel plate: } 3,410 \text{ lb at } \$0.10 \quad 341.00$$

¹Subscripts 1 and 2 refer to upper and lower truncated cones that form the truncated section. The term, $r_1^2 (h_2 - h_1)$, is necessary because the truncated section and spherical segment overlap.

Fabrication and erection of compartment lining		\$ 400.00
Fan with motor, 3,000 cfm at 2" static pressure (installed and connected to generator):		650.00
Duct work, inlet and outlet:		
4.5 ft, 14" pipe at \$5.00 = \$22.50		
Fabricated and installed = <u>25.00</u>		
\$47.50		48.00
Blast protection (installed):		2600.00
Blast protection on exhaust (installed):		200.00
	Subtotal	<u>\$8365.00</u>
	10% overhead & 10% contingency	<u>1673.00</u>
	Total	\$10038.00

Appendix B

AIR-COOLING REQUIREMENTS

From reference 6 (page 443), the energy input for a typical diesel engine is distributed as follows:

Brake horsepower (useful work)	30%
Cooling water loss	28%
Dry exhaust loss	24%
Hydrogen-moisture loss	9%
Radiation and unaccounted for	9%

Both the dry exhaust loss and the hydrogen-moisture loss are removed by the exhaust system. The diesel engine drives a generator which may be 85 percent efficient. Since the selected output of the generator is 10 kw, the required brake horsepower from the driver is:

$$\frac{10 \text{ kw}}{(0.85) (0.746)} = 15.78 \text{ HP}$$

and the input to the driver is:

$$\frac{(15.78 \text{ HP}) (2,544)}{(0.30)} = 134,000 \text{ BTU/hr}$$

The cooling water loss (28%) and radiation loss (9%) as well as 15% of the generator input ($0.30 \times 15\% = 4\frac{1}{2}\%$) contribute to the heat that escapes into the generator compartment, or $41\frac{1}{2}\%$ of 134,000 = 55,600 BTU/hr.

From reference 7 (equation 5, page 144):

$$q = Q \times 1.08 (t_i - t_o)$$

where q = heat removed, BTU per hour

Q = air required, cfm

$t_i - t_o$ = temperature difference, deg F

Since most engines, motors and similar equipment are designed to operate under ambient conditions of not more than 120 to 130°F, a 20 degree rise in air temperature is about all that can be allowed; even then, special air cooling may be necessary during a desert summer. Thus, if the outside air is 100°F, the air in the engine compartment will be about 120°F. Under these conditions, Q is given by $55,600 = Q (1.08 \times 20)$.

Thus, $Q = 2,575$ cfm or approximately 2,600 cfm.

If only a 10° rise in temperature is allowable, Q will, of course, be twice this value or 5,150 cfm. This is the 5,200 cfm used in the text for the discussion of the generator in the shelter.

Appendix C

EXHAUST HAZARDS

The following discussion assumes that the generators will be diesel-powered. If a gasoline generator is used, the hazard is greater because the exhaust will contain more carbon monoxide. The concentration of carbon dioxide determines the minimum ventilation requirements for diesels. Since this discussion concludes that a separate exhaust outlet is necessary, special consideration of the carbon monoxide output of gasoline generators is unnecessary.

From reference 8 (page 51),

$$Q = V \frac{c}{Y}$$

where Q = volume of normal air required for ventilation, cfm

V = volume of exhaust gas produced by the engine, cfm

c = the concentration in the exhaust gas of the particular toxic constituent under consideration, percent by volume

Y = the maximum hygienically safe concentration for the particular toxic constituent under consideration, percent by volume

The values V and c are determined by engine tests. But since it is not known which diesel generator will be used, the values in reference 8 are assumed to be typical. This reference also suggests multiplying Q by a factor of 2 because the effects of several toxic agents are cumulative. The criteria from reference 8 are maximum for the safety of an individual working in a mine for 8 hours -- a situation not too different from shelter occupancy.

If the volume of exhaust gas is 100 cfm, which is typical of small diesel engines, and the carbon dioxide content is 14 percent by volume,

$$Q = 100 \frac{(14)}{(0.5)} = 2,800 \text{ cfm}$$

In this calculation, 0.5 is the maximum percentage of carbon dioxide allowable. Carbon dioxide is used for this calculation because it gives the largest air requirement of the toxic constituents in the exhaust.

Applying the factor of 2, it would take 5,600 cfm of ventilating air to remove exhaust gases for safe habitation of the compartment, more than twice that calculated in Appendix B for cooling alone. Thus, it is not economical to remove the exhaust with ventilating air, and a separate exhaust outlet is necessary.

Appendix D

AIR-COMBUSTION REQUIREMENTS

A 10 kw generator requires a driver in the 15 to 20 bhp range. A piston displacement of 150 cubic inches is typical for an engine of this size. At 1,800 rpm, the airflow rate for a 4-cycle diesel engine is:

$$\frac{(150)}{(1728)} \text{ ft}^3/\text{cycle} (1,800 \text{ rev/min}) (\frac{1}{2} \text{ cycle/rev}) = 78 \text{ cfm}$$

This amount of air, which may be included in the ventilation air, is small compared to the 2,600 cfm of air required for cooling. The calculation is conservative (the airflow is high) because the volumetric efficiency is assumed to be 100 percent. Since the airflow is throttled in a gasoline engine, it consumes less air, perhaps only half as much as a diesel engine whose airflow is not throttled.

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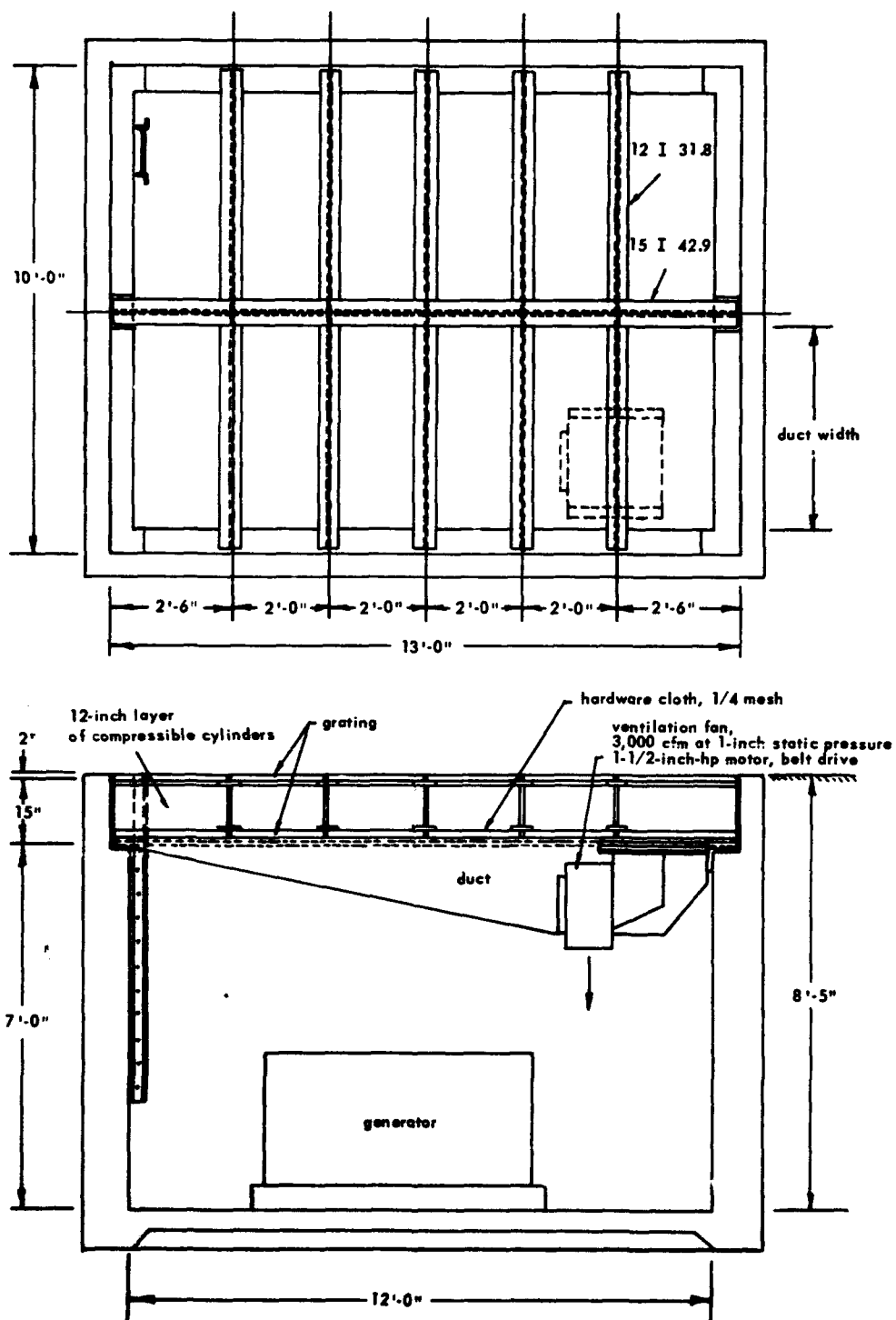


Figure 1. Generator compartment -- pit with filter cover

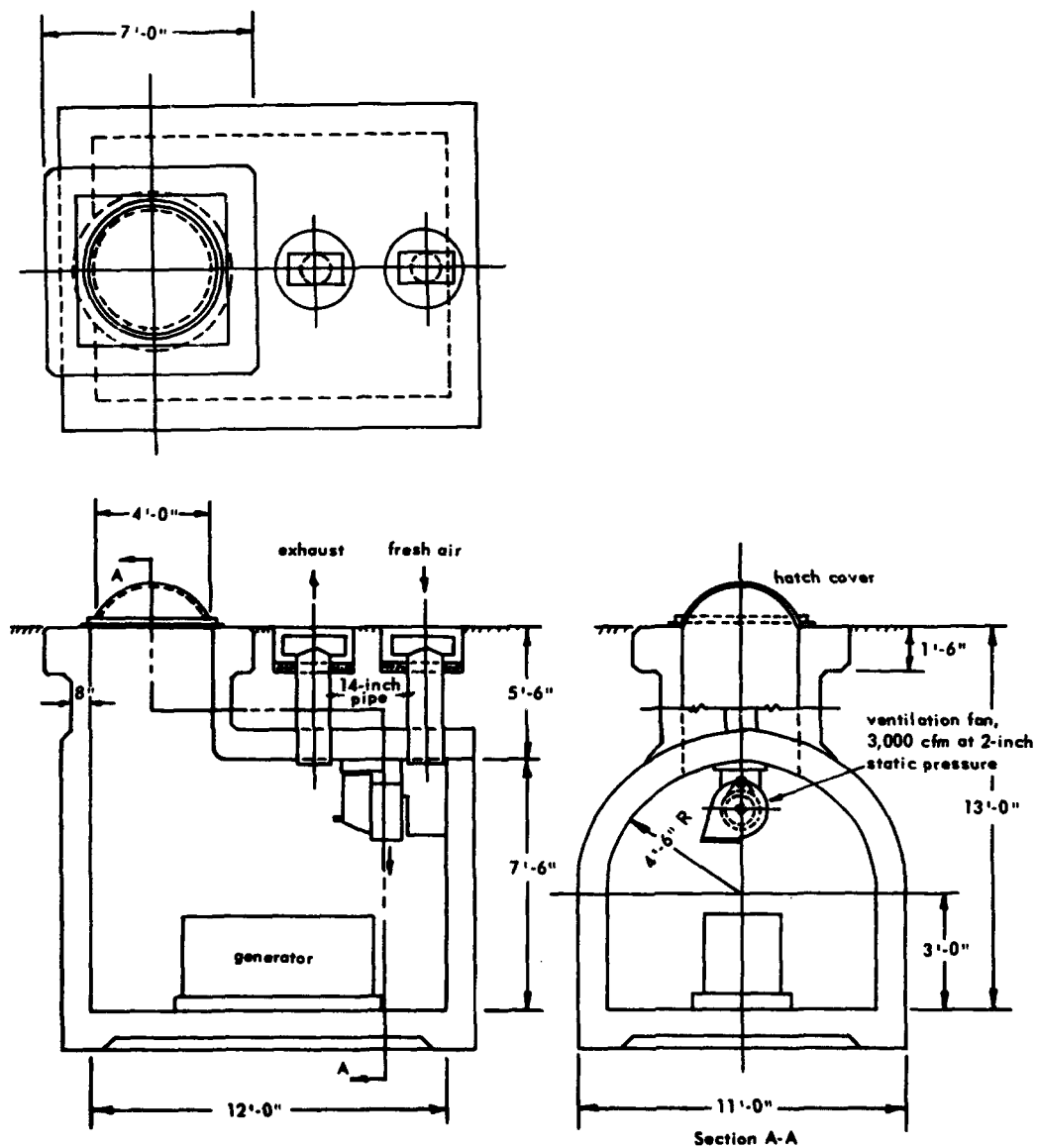


Figure 2. Generator compartment -- underground chamber

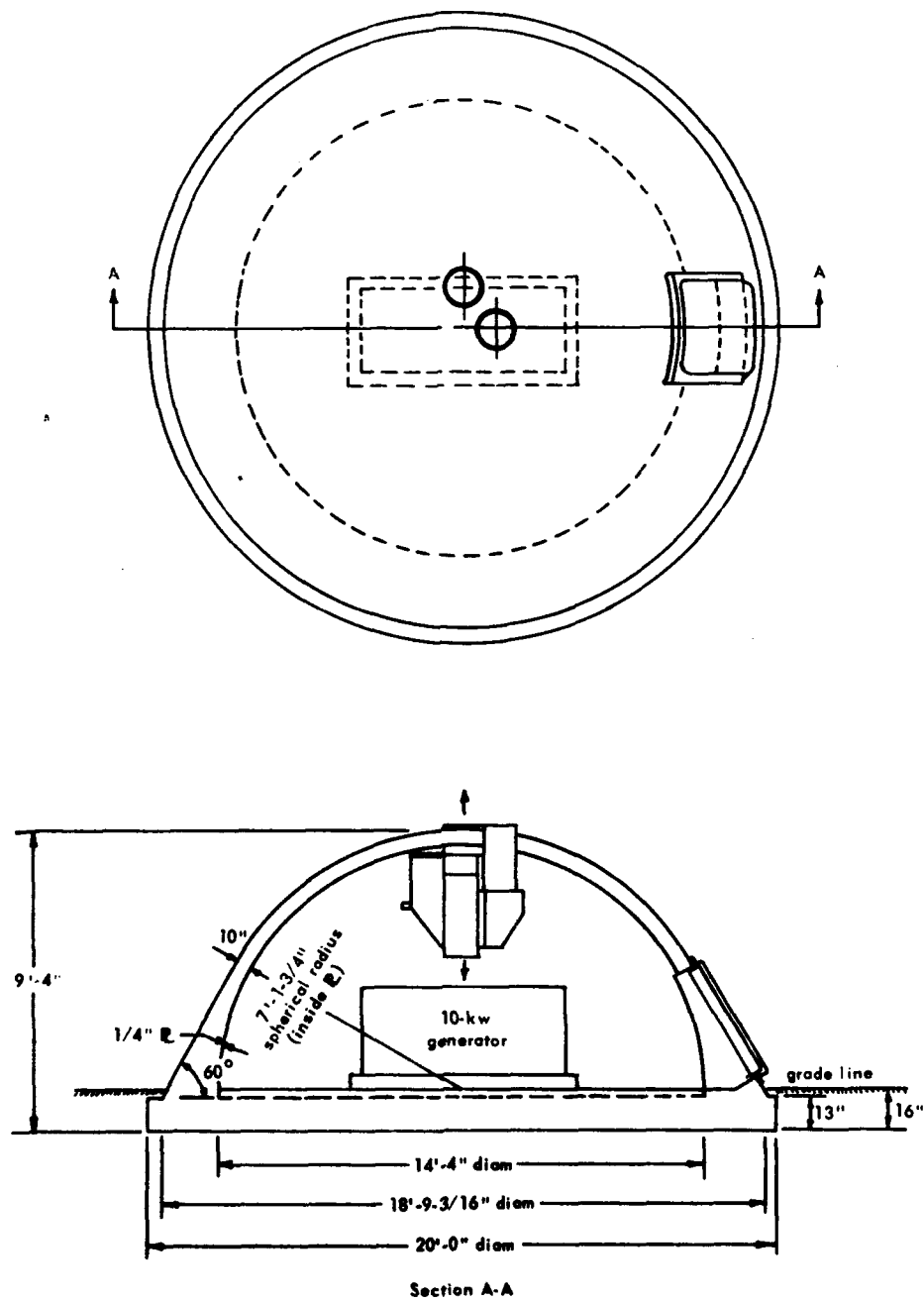


Figure 3. Generator compartment -- above ground bunker